

# String Theory at LHC Using Jet Production From String Regge Excitations vs String Balls

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## Abstract

If we find extra dimensions in the second run of the LHC in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV, then the string mass scale  $M_s$  can be  $\sim$  TeV and we should produce QCD jets in  $2 \rightarrow 2$  partonic collisions via string Regge excitations at the LHC. QCD jets can also be produced from string balls via thermal radiation at Hagedorn temperature. In this paper we study jet production from string Regge excitations vs string balls in  $pp$  collisions at  $\sqrt{s} = 14$  TeV at LHC and make a comparison with the standard model QCD jets. We find that high  $p_T$  jet production from string Regge excitations can be larger than that from string balls and from standard model QCD jets. We also find resonances in the jet production cross section in string Regge excitation scenario which is absent in the other two scenarios. Hence TeV scale high  $p_T$  jets can be a good signature to study string Regge excitations in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV at the LHC.

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## I. INTRODUCTION

If extra dimensions [1, 2] are found at the LHC in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV, then the string mass scale  $M_s$  could be around  $\sim$  TeV and we should produce: 1) string Regge excitations [3–5], 2) string balls [6–9] and 3) black holes [10–15] in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV at the LHC. Note that in the first run at LHC in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and 8 TeV we have not found any experimental evidence of beyond standard model physics at LHC [16]. LHC has started its second run with  $pp$  collisions at  $\sqrt{s} = 13$  TeV and it will achieve its maximum energy of  $pp$  collisions at  $\sqrt{s} = 14$  TeV in future. Hence all our analysis in this paper will be at the maximum energy at LHC, *i. e.*, we will perform our calculation in this paper for  $pp$  collisions at  $\sqrt{s} = 14$  TeV at LHC. LHC in its second run will also collide two lead nuclei at  $\sqrt{s} = 5.5$  TeV per nucleon which will achieve the total energy  $\sim 1150$  TeV to produce quark-gluon plasma [17, 18] where we may expect to observe new physics [19].

The string Regge excitations with masses of order  $M_s$  can be searched in  $2 \rightarrow 2$  partonic processes in  $pp$  collisions at LHC in the weak coupling limit in a model independent framework [5]. In this case a whole tower of infinite string excitations will open up and the new particles follow the Regge trajectories of vibrating string

$$j = j_0 + \alpha' M^2 \quad (1)$$

with spin  $j$  where the Regge slope parameter  $\alpha'$  determines the fundamental string mass scale [5]

$$\alpha' = \frac{1}{M_{\text{string}}^2}. \quad (2)$$

These stringy states will lead to new contributions to standard model scattering processes. This is based on the extensions of standard model where open strings ends on D-branes, with gauge bosons due to strings attached to stacks of D-branes and chiral matter due to strings stretching between intersecting D-branes [3]. Using this idea recently dijet production amplitude is calculated in  $2 \rightarrow 2$  partonic collisions. Since the string Regge resonances occur around  $M_s$  we expect an enhancement of TeV scale jet production at CERN LHC from string Regge excitations.

String theory is also studied at LHC via string ball production [6, 7, 13]. A string ball is a highly excited long string which emits massless (and massive) particles at Hagedorn

temperature with thermal spectrum [8, 20]. In string theory the string ball mass  $M_{SB}$  is larger than the string mass scale  $M_s$  [21, 22]. Typically

$$M_s < M_{SB} < \frac{M_s}{g_s^2} \quad (3)$$

where  $g_s$  is the string coupling which can be less than 1 for the string perturbation theory to be valid. The Hagedorn temperature of a string ball is given by

$$T_{SB} = \frac{M_s}{\sqrt{8\pi}}. \quad (4)$$

Since this temperature is very high at LHC ( $\sim$  hundreds of GeV) we also expect an enhancement of TeV scale jet production at CERN LHC from string balls.

In this paper we study jet production from string balls and from string Regge excitations at LHC and make a comparison with the standard model QCD jets. We find that high  $p_T$  jet production from string Regge excitations can be larger than that from string balls and from standard model QCD jets. We also find resonances in the jet production cross section in string Regge excitation scenario which is absent in the other two scenarios. Hence TeV scale high  $p_T$  jets can be a good signature to study string Regge excitations at LHC.

The paper is organized as follows. In section II we describe QCD jet production via string Regge excitations in  $2 \rightarrow 2$  parton fusion processes at LHC. In section III we describe jet production from string balls at LHC. We present our results and discussions in section IV and conclude in section V.

## II. JET PRODUCTION IN $2 \rightarrow 2$ PROCESSES VIA STRING REGGE EXCITATIONS

The string Regge excitations with masses of order  $M_s$  can be searched in  $2 \rightarrow 2$  partonic processes in pp collisions at LHC in the weak coupling limit in a model independent framework [5]. The  $2 \rightarrow 2$  partonic scattering amplitudes via string Regge excitations can be computed by using string perturbation theory. At leading order one finds

$$\begin{aligned} |M(gg \rightarrow gg)|^2 = & \frac{19}{12} \frac{16\pi^2 \alpha_s^2}{M_s^4} \times [W_{g^*}^{gg \rightarrow gg} \left[ \frac{\hat{s}^4}{(\hat{s} - M_s^2)^2 + (\Gamma_{g^*}^{J=0} M_s)^2} + \frac{(\hat{u}^4 + \hat{t}^4)}{(\hat{s} - M_s^2)^2 + (\Gamma_{g^*}^{J=2} M_s)^2} \right] \\ & + W_{C^*}^{gg \rightarrow gg} \left[ \frac{\hat{s}^4}{(\hat{s} - M_s^2)^2 + (\Gamma_{C^*}^{J=0} M_s)^2} + \frac{(\hat{u}^4 + \hat{t}^4)}{(\hat{s} - M_s^2)^2 + (\Gamma_{C^*}^{J=2} M_s)^2} \right]], \end{aligned} \quad (5)$$

$$|M(gg \rightarrow q\bar{q})|^2 = \frac{7}{24} \frac{16\pi^2\alpha_s^2}{M_s^4} N_f \times \\ [W_{g^*}^{gg \rightarrow q\bar{q}} \frac{\hat{u}\hat{t}(\hat{u}^2 + \hat{t}^2)}{(\hat{s} - M_s^2)^2 + (\Gamma_{g^*}^{J=2} M_s)^2} + W_{C^*}^{gg \rightarrow q\bar{q}} \frac{\hat{u}\hat{t}(\hat{u}^2 + t^2)}{(\hat{s} - M_s^2)^2 + (\Gamma_{C^*}^{J=2} M_s)^2}], \quad (6)$$

$$|M(q\bar{q} \rightarrow gg)|^2 = \frac{56}{27} \frac{16\pi^2\alpha_s^2}{M_s^4} \times \\ [W_{g^*}^{q\bar{q} \rightarrow gg} \frac{\hat{u}\hat{t}(\hat{u}^2 + \hat{t}^2)}{(\hat{s} - M_s^2)^2 + (\Gamma_{g^*}^{J=2} M_s)^2} + W_{C^*}^{q\bar{q} \rightarrow gg} \frac{\hat{u}\hat{t}(\hat{u}^2 + t^2)}{(\hat{s} - M_s^2)^2 + (\Gamma_{C^*}^{J=2} M_s)^2}] \quad (7)$$

and

$$|M(qg \rightarrow qg)|^2 = -\frac{4}{9} \frac{16\pi^2\alpha_s^2}{M_s^2} \times [\frac{\hat{u}\hat{s}^2}{(\hat{s} - M_s^2)^2 + (\Gamma_{q^*}^{J=1/2} M_s)^2} + \frac{\hat{u}^3}{(\hat{s} - M_s^2)^2 + (\Gamma_{q^*}^{J=3/2} M_s)^2}]. \quad (8)$$

Here  $\hat{s}$ ,  $\hat{t}$  and  $\hat{u}$  are the Mandelstam variables at partonic level. For massless partons,  $\hat{s} + \hat{t} + \hat{u} = 0$  in the  $2 \rightarrow 2$  partonic scattering processes. In the above expressions  $\alpha_s$  is the QCD coupling constant and

$$W_{g^*}^{gg \rightarrow gg} = 0.09, \quad W_{C^*}^{gg \rightarrow gg} = 0.91, \quad W_{g^*}^{gg \rightarrow q\bar{q}} = W_{g^*}^{q\bar{q} \rightarrow gg} = 0.24, \quad W_{C^*}^{gg \rightarrow q\bar{q}} = W_{C^*}^{q\bar{q} \rightarrow gg} = 0.76; \\ \Gamma_{g^*}^{J=2} = 45(M_s/\text{TeV})\text{GeV}, \quad \Gamma_{g^*}^{J=0} = \Gamma_{C^*}^{J=2} = 75(M_s/\text{TeV})\text{GeV}, \\ \Gamma_{C^*}^{J=0} = 150(M_s/\text{TeV})\text{GeV}, \quad \Gamma_{q^*}^{J=1/2} = \Gamma_{q^*}^{J=1/2} = 37(M_s/\text{TeV})\text{GeV}. \quad (9)$$

The  $\frac{d\sigma}{dp_T}$  of jet production at LHC is given by

$$\frac{d\sigma}{dp_T} = \sum_{a,b} \frac{p_T}{8\pi s} \int dy \int dy_2 \frac{1}{\hat{s}} f_a(x_1, Q^2) f_b(x_2, Q^2) \times |M(ab \rightarrow cd)|^2 \quad (10)$$

where  $a, b = q, \bar{q}, g$  and

$$x_1 = \frac{p_T}{\sqrt{s}}[e^y + e^{y_2}], \quad x_2 = \frac{p_T}{\sqrt{s}}[e^{-y} + e^{-y_2}]. \quad (11)$$

We have used CTEQ6M sets [23] for the parton distribution function  $f(x, Q^2)$  inside the proton at LHC. We choose the factorization and renormalization scales to be  $Q = p_T$  of the jet.

### III. JET PRODUCTION FROM STRING BALLS AT LHC

For small string coupling  $g_s < 1$  the Planck length  $l_P$  and the quantum length scale of the string  $l_s$  are related by

$$l_P^{n+2} \sim g_s^2 l_s^{n+2} \quad (12)$$

where  $n$  is the number of extra dimensions. According to string theory as black hole shrinks it reaches the correspondence point [21, 22]

$$M \leq M_{\text{correspondence}} \sim \frac{M_s}{g_s^2}, \quad M_s \sim \frac{1}{l_s}, \quad (13)$$

and makes a transition to a configuration dominated by a highly excited long string known as string ball. The string ball continues to lose mass by evaporation at the Hagedorn temperature [20]. Hence the conventional description of evaporation in terms of black body radiation can be applied. The average radius of the string ball is given by

$$R_{SB} \sim \frac{1}{M_s} \sqrt{\frac{M_{SB}}{M_s}}. \quad (14)$$

Production of a highly excited string from the collision of two light string states at high  $\sqrt{s}$  can be obtained from the Virasoro-Shapiro four point amplitude by using string perturbation theory. One finds the amplitude

$$A(s, t) = \frac{2\pi g_s^2 \Gamma[-1 - \alpha's/4] \Gamma[-1 - \alpha't/4] \Gamma[-1 - \alpha'u/4]}{\Gamma[2 + \alpha's/4] \Gamma[2 + \alpha't/4] \Gamma[2 + \alpha'u/4]} \quad (15)$$

with

$$s + t + u = -16/\alpha', \quad \alpha' = l_s^2. \quad (16)$$

The production cross section is

$$\hat{\sigma} \sim \frac{\pi \text{Res} A(\alpha's/4 = N, t = 0)}{s} = g_s^2 \frac{\pi^2}{8} \alpha'^2 s. \quad (17)$$

This cross section saturates the unitarity bounds at around  $g_s^2 \alpha's \sim 1$  (or  $s \sim \frac{M_s^2}{g_s^2}$ ). This implies that the production cross section for string ball grows with  $s$  as in eq. (17) only for  $M_s \ll \sqrt{s} \ll M_s/g_s$  while for  $\sqrt{s} >> M_s/g_s$  we find  $\sigma_{SB} = l_s^2$  which is constant. Hence the string ball production cross section in a parton-parton collision is given by

$$\begin{aligned} \hat{\sigma}_{SB} &= g_s^2 \frac{\pi^2}{8} \alpha'^2 s \sim \frac{g_s^2 M_{SB}^2}{M_s^4}, & M_s \ll M_{SB} \ll M_s/g_s, \\ \hat{\sigma}_{SB} &= l_s^2 \sim \frac{1}{M_s^2}, & M_s/g_s \ll M_{SB} \ll M_s/g_s^2. \end{aligned} \quad (18)$$

If string balls are formed at the LHC then they will quickly evaporate by emitting massless (and massive) particles at Hagedorn temperature with thermal spectrum [7, 8, 20]. The

emission rate for jets with momentum  $\vec{p}$  and energy  $E$  from a string ball of temperature  $T_{SB}$  is given by

$$\frac{dN_{\text{jet}}}{d^3pd^t} = \frac{A_n c_n}{32\pi^3} \frac{1}{(e^{\frac{E}{T_{SB}}} \pm 1)}, \quad (19)$$

where  $A_n$  is the  $d (= n+3)$  dimensional area factor [7, 9, 25] and  $c_n$  is the multiplicity factor.  $c_n = 16$  for gluon and  $c_n = 6$  for a single flavor quark. The  $+$  ( $-$ ) sign is for quark (gluon) jets.

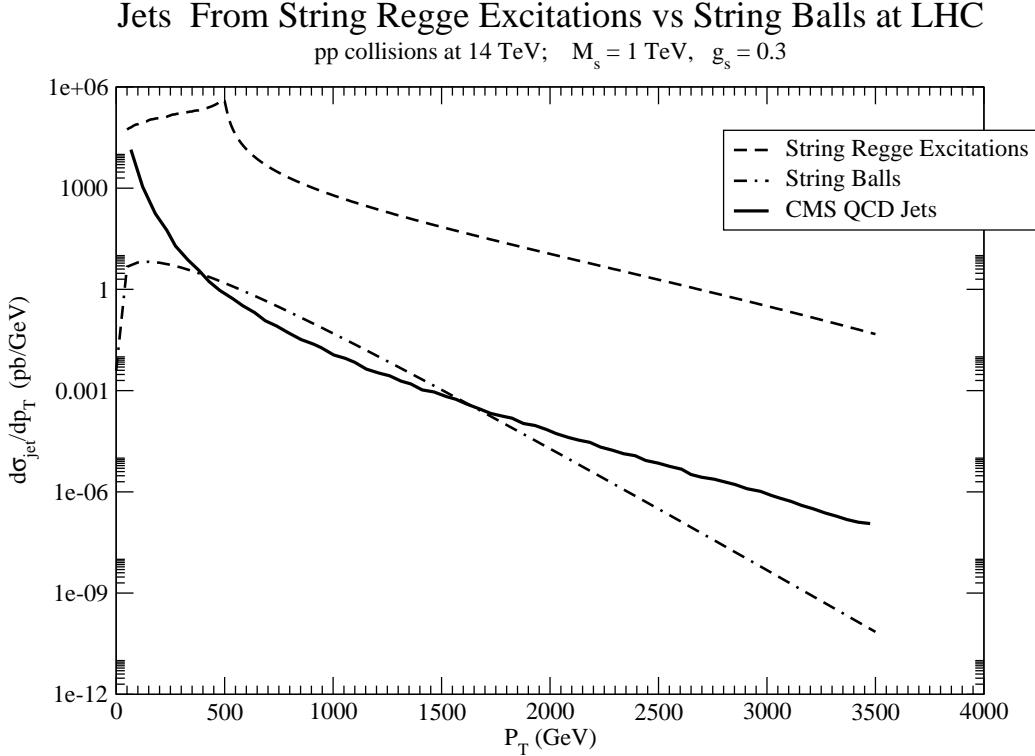


FIG. 1:  $p_T$  distribution of jet production cross section from string Regge excitations, from string balls and from standard model QCD processes in pp collisions at  $\sqrt{s} = 14$  TeV at LHC. The string mass scale  $M_s = 1$  TeV.

The differential cross section for gluon jet production with momentum  $\vec{p}$  and energy  $E = \sqrt{\vec{p}^2}$  from string ball of temperature  $T_{SB}$  at LHC is given by [7, 24]

$$\frac{Ed\sigma_{\text{gluon}}}{d^3p} = \frac{1}{(2\pi)^3 s} \sum_{ab} \int_{M_s^2}^{\frac{M_s^2}{g_s^4}} dM^2 \int \frac{dx_a}{x_a} f_{a/p}(x_a, \mu^2) f_{b/p}\left(\frac{M^2}{sx_a}, \mu^2\right) \hat{\sigma}^{ab}(M) \frac{A_n c_n \gamma \tau_{SB} p^\mu u_\mu}{(e^{\frac{p^\mu u_\mu}{T_{SB}}} - 1)}, \quad (20)$$

where  $M_s$  is the string mass scale and  $g_s$  is the string coupling which is less than 1 for the string perturbation theory to be valid, see eq. (3). The flow velocity is  $u^\mu$  and  $\gamma$  is the

Lorentz boost factor with

$$\gamma \vec{v}_{SB} = (0, 0, \frac{(x_1 - x_2)\sqrt{s}}{2M_{SB}}). \quad (21)$$

$A_n$  is the  $d (= n + 3)$  dimensional area factor [7, 25]. We will use the number of extra dimensions  $n = 6$  in our calculation. The partonic level string ball production cross section is given by [6]

$$\begin{aligned} \hat{\sigma}(M_{SB}) &= \frac{1}{M_s^2}, & \frac{M_s}{g_s} < M_{SB} &< \frac{M_s}{g_s^2} \\ \hat{\sigma}(M_{SB}) &= \frac{g_s^2 M_{SB}^2}{M_s^4}, & M_s < M_{SB} &< \frac{M_s}{g_s}. \end{aligned} \quad (22)$$

We have used CTEQ6M PDF [23] in our calculation.

Similarly, the differential cross section for quark jet production with momentum  $\vec{p}$  and energy  $E = \sqrt{\vec{p}^2}$  from string ball of temperature  $T_{SB}$  at LHC is given by

$$\frac{Ed\sigma_{\text{quark}}}{d^3p} = \frac{1}{(2\pi)^3 s} \sum_{ab} \int_{M_s^2}^{\frac{M_s^2}{g_s^4}} dM^2 \int \frac{dx_a}{x_a} f_{a/p}(x_a, \mu^2) f_{b/p}\left(\frac{M^2}{sx_a}, \mu^2\right) \hat{\sigma}^{ab}(M) \frac{A_n c_n \gamma \tau_{SB} p^\mu u_\mu}{(e^{\frac{p^\mu u_\mu}{T_{SB}}} + 1)}. \quad (23)$$

#### IV. RESULTS AND DISCUSSIONS

In this section we present results of jet production cross section in pp collisions at  $\sqrt{s}=14$  TeV at LHC from string Regge excitations and from string balls. We make a comparison with the standard model QCD jets at the LHC. We use

$$g_s = 0.3 \quad (24)$$

in our calculation [8].

In Fig. 1 we present  $\frac{d\sigma}{dp_T}$  of jet production from string Regge excitations, from string balls and make a comparison with the standard model QCD jets at the LHC in pp collisions at  $\sqrt{s}=14$  TeV. We use the string mass scale  $M_s = 1$  TeV in our calculation. The dashed line is for jet production from string Regge excitations at LHC. The dot-dashed line is for jet production from string balls at LHC. For comparison we present  $\frac{d\sigma}{dp_T}$  of standard model QCD jets in the solid line at LHC from [26]. It can be seen that if the string mass scale  $M_s \sim 1$  TeV, then jet production from string Regge excitations is much larger than standard

## Jets From String Regge Excitations vs String Balls at LHC

pp collisions at 14 TeV;  $M_s = 2 \text{ TeV}$ ,  $g_s = 0.3$

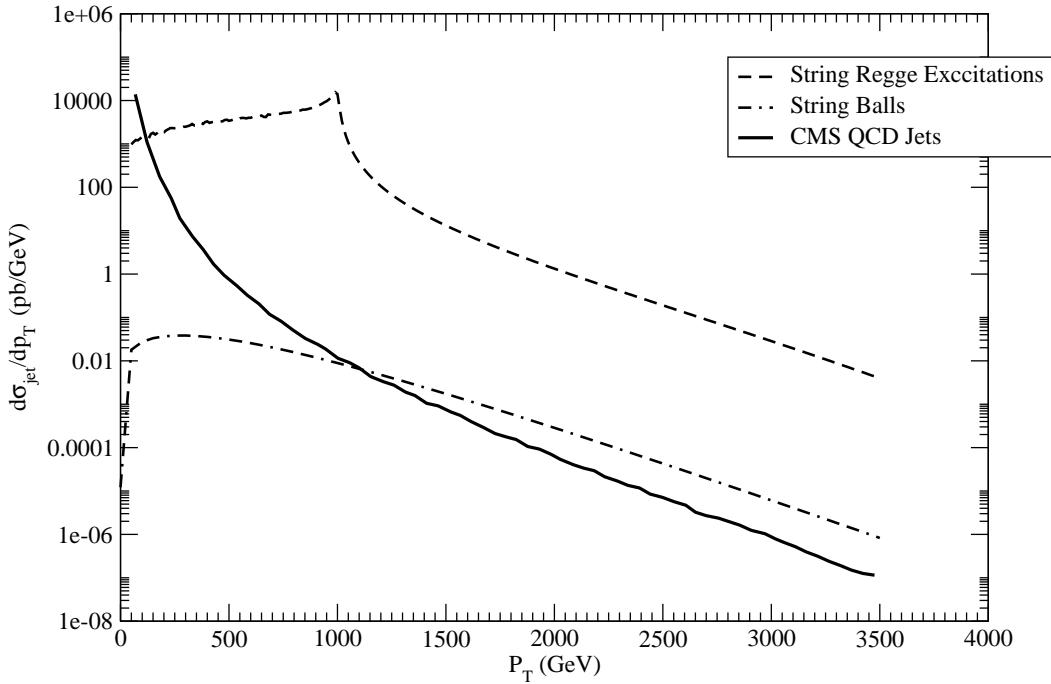


FIG. 2:  $p_T$  distribution of jet production cross section from string Regge excitations, from string balls and from standard model QCD processes in pp collisions at  $\sqrt{s} = 14 \text{ TeV}$  at LHC. The string mass scale  $M_s = 2 \text{ TeV}$ .

model QCD jets and also that from string balls at LHC. It can also be seen that there are resonances in the jet production cross section in the string Regge excitation scenario which is absent in other two scenarios. Hence TeV scale high  $p_T$  jet can be a good signature to study string string Regge excitations at LHC.

In Fig. 2 we present  $\frac{d\sigma}{dp_T}$  of jet production from string Regge excitations, from string balls and make a comparison with the standard model QCD jets at the LHC in pp collisions at  $\sqrt{s}=14 \text{ TeV}$  for string mass scale  $M_s = 2 \text{ TeV}$ . The dashed line is for jet production from string Regge excitations at LHC. The dot-dashed line is for jet production from string balls at LHC. For comparison we present  $\frac{d\sigma}{dp_T}$  of standard model QCD jets in the solid line at LHC from [26]. It can be seen that if the string mass scale  $M_s \sim 2 \text{ TeV}$ , then high  $p_T$  jet production ( $p_T > 100 \text{ GeV}$ ) from string Regge excitations can be much larger than standard model QCD jets. It can also be seen that if the string mass scale  $M_s \sim 2 \text{ TeV}$ , then jet production from string Regge excitations can be much larger than the jet production from

## Jets From String Regge Excitations vs String Balls at LHC

pp collisions at 14 TeV;  $M_s = 4 \text{ TeV}$ ,  $g_s = 0.3$

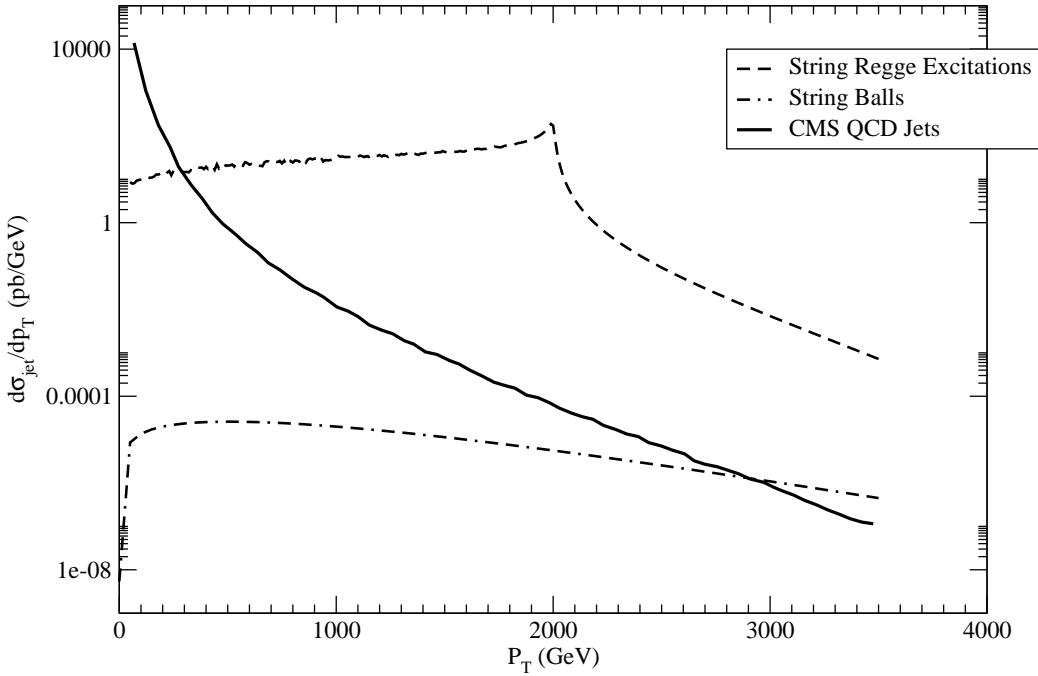


FIG. 3:  $p_T$  distribution of jet production cross section from string Regge excitations, from string balls and from standard model QCD processes in pp collisions at  $\sqrt{s} = 14 \text{ TeV}$  at LHC. The string mass scale  $M_s = 4 \text{ TeV}$ .

string balls at LHC. For  $p_T \lesssim 1 \text{ TeV}$ , the standard model jet production is higher than the jet produced from string balls at LHC, whereas for  $p_T \gtrsim 1 \text{ TeV}$  the jet production from string balls at LHC is higher than the jets produced from standard model processes at LHC. It can also be seen that there are resonances in the jet production cross section in the string Regge excitation scenario which is absent in other two scenarios. Hence TeV scale high  $p_T$  jet can be a good signature to study string Regge excitations at LHC.

In Fig. 3 we present  $\frac{d\sigma}{dp_T}$  of jet production from string Regge excitations, from string balls and make a comparison with the standard model QCD jets at the LHC in pp collisions at  $\sqrt{s}=14 \text{ TeV}$  for string mass scale  $M_s = 4 \text{ TeV}$ . The dashed line is for jet production from string Regge excitations at LHC. The dot-dashed line is for jet production from string balls at LHC. For comparison we present  $\frac{d\sigma}{dp_T}$  of standard model QCD jets in the solid line at LHC from [26]. It can be seen that if the string mass scale  $M_s \sim 4 \text{ TeV}$ , then high  $p_T$  jet production ( $p_T > 300 \text{ GeV}$ ) from string Regge excitations can be much larger than standard

## Jets From String Regge Excitations vs String Balls at LHC

pp collisions at 14 TeV; Luminosity= 10/pb;  $g_s = 0.3$

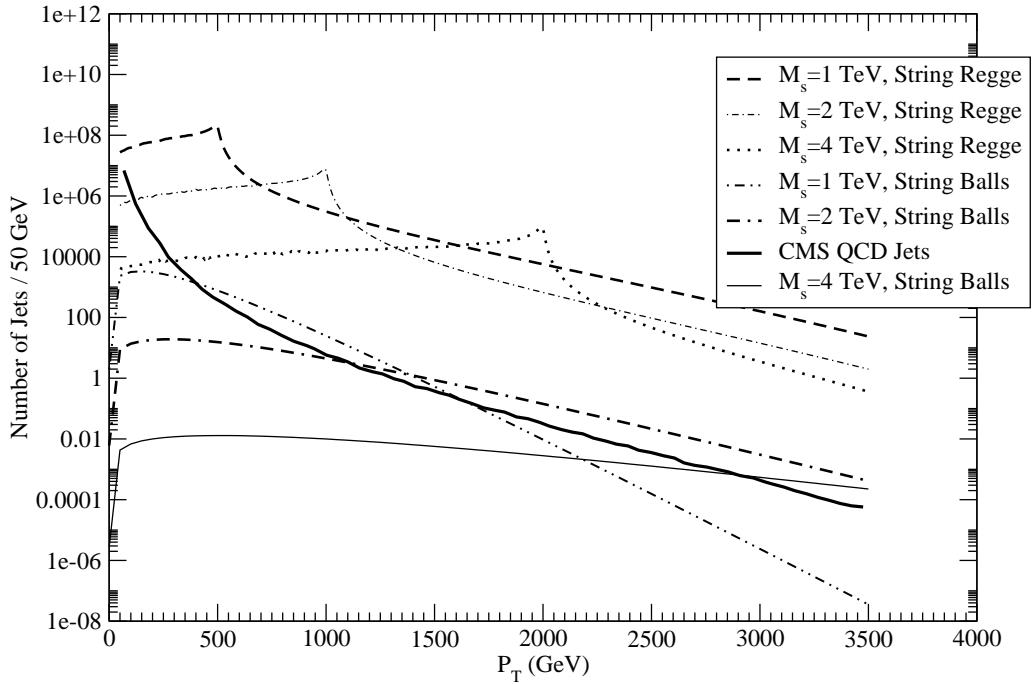


FIG. 4:  $p_T$  distribution of number of jet production from string Regge excitations, from string balls and from standard model QCD processes in pp collisions at  $\sqrt{s} = 14$  TeV at LHC with luminosity equals to  $10 pb^{-1}$ .

model QCD jets. It can also be seen that if the string mass scale  $M_s \sim 4$  TeV, then jet production from string Regge excitations can be much larger than the jet production from string balls at LHC. For  $p_T \lesssim 3$  TeV, the standard model jet production is higher than the jet produced from string balls at LHC, whereas for  $p_T \gtrsim 3$  TeV the jet production from string balls at LHC is higher than the jets produced from standard model processes at LHC. It can also be seen that there are resonances in the jet production cross section in the string Regge excitation scenario which is absent in other two scenarios. Hence TeV scale high  $p_T$  jet can be a good signature to study string Regge excitations at LHC.

In Fig. 4 we present number of jet production per  $p_T$  (in 50 GeV  $p_T$  bin) from string Regge excitations, from string balls for various values of  $M_s$  and make a comparison with the standard model QCD jets at LHC. The dashed, dot-dashed and dotted lines are for jets from string Regge excitations at LHC with string mass scale  $M_s = 1, 2$  and  $4$  TeV respectively. The dot-dot-dashed, dot-dashed-dashed and thin solid lines are for jets from string balls at

LHC with string mass scale  $M_s = 1, 2$  and  $4$  TeV respectively. For comparison we present standard model results for QCD jets in the solid line at LHC from [26]. It can be seen that, depending on the values of the string mass scale  $M_s$ , the jets from string Regge excitations can be much larger than standard model QCD jets and also that from string balls at LHC. It can also be seen that there are resonances in the jet production cross section in the string Regge excitation scenario which is absent in other two scenarios.

Hence we find that TeV scale high  $p_T$  jet can be a good signature to study string string Regge excitations at LHC.

## V. CONCLUSIONS

If we find extra dimensions in the second run of the LHC in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV, then the string mass scale  $M_s$  can be  $\sim$  TeV and we should produce QCD jets in  $2 \rightarrow 2$  partonic collisions via string Regge excitations at the LHC. QCD jets can also be produced from string balls via thermal radiation at Hagedorn temperature. In this paper we have studied jet production from string Regge excitations vs string balls in  $pp$  collisions at  $\sqrt{s} = 14$  TeV at LHC and have made a comparison with the standard model QCD jets. We have found that high  $p_T$  jet production from string Regge excitations can be larger than that from string balls and from standard model QCD jets. We have also found resonances in the jet production cross section in string Regge excitation scenario which is absent in the other two scenarios. Hence TeV scale high  $p_T$  jets can be a good signature to study string Regge excitations in the  $pp$  collisions at  $\sqrt{s} = 14$  TeV at the LHC.

LHC in its second run will also collide two lead nuclei at  $\sqrt{s} = 5.5$  TeV per nucleon which will achieve the total energy  $\sim 1150$  TeV to produce quark-gluon plasma [17, 18, 27, 28] where we may expect to observe new physics [19, 20, 25].

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